Accelerating the Development of Expandable Liner Hanger Systems using Abaqus

Ganesh Nanaware, Tony Foster, Leo Gomez

Baker Hughes Incorporated

Abstract: Developing an expandable liner hanger system for the oil and gas industry represents an engineering challenge. Finite element analysis (FEA) using Abaqus can be effective at reducing development time and cost, and for optimizing the design with fewer prototypes.

This paper summarizes the use of Abaqus/Explicit for FEA of an expandable liner hanger system that comprises an adjustable swage to expand the hanger body, slip ring to hang, and a packer to seal in a variable-diameter casing. Using the Abaqus-based FEA results, potential designs were evaluated on performance parameters such as required expansion force, hanging capacity, wickers penetration, and seal integrity. Arbitrary Lagrangian Eulerian (ALE) adaptive meshing is used to simulate the wicker penetration to the casing. As friction between the hanger body and swage produced significant impact on the performance, a sensitivity study was performed to represent proper friction values as corroborated by physical test data.

Despite some analytical challenges, Abaqus Explicit has been successfully used to optimize the design of the adjustable swage for each casing weight range during the design of an expandable liner hanger system. It helped us study the effect of various design parameters of the adjustable swage on sealing integrity, hanging capacity, and other performance targets before prototype testing, hence reducing the number of prototype tests. In summary, FEA using Abaqus helped us to reduce the development time and cost and improve the reliability of an expandable liner hanger system.

Keywords: Expandable, Liner Hanger, Oil and Gas, FEA, Explicit, Optimization, DOE

1. Introduction

The oil and gas industry is turning to more extreme drilling environments including offshore deep-water exploration and onshore shale oil exploration, which has many technical challenges due to higher depth, extreme pressure and temperature, and unconventional geological variations. The expandable liner hanger is a liner hanger system capable of hanging liner weight under extreme conditions thereby allowing wellbore construction through these problematic environments. The expandable liner hanger uses pipe expansion, in place of conventional mechanisms, for making contact with the casing wall to support the weight of the liner and seal off the annulus. The expandable liner hanger system as shown in Figure 1 comprises a hanger body, slip ring, and a packer. A special running tool with an adjustable swage is used to carry the system into the well and through applied hydraulic pressure the adjustable swage moves and plastically deforms the hanger body to activate both the slips and the packer. Both the hanging slips and packer are

forced outward during expansion causing them to make contact with the parent casing wall. After the expansion is complete, the running tool is removed from the wellbore leaving the liner hanger and the suspended liner in place in the well.
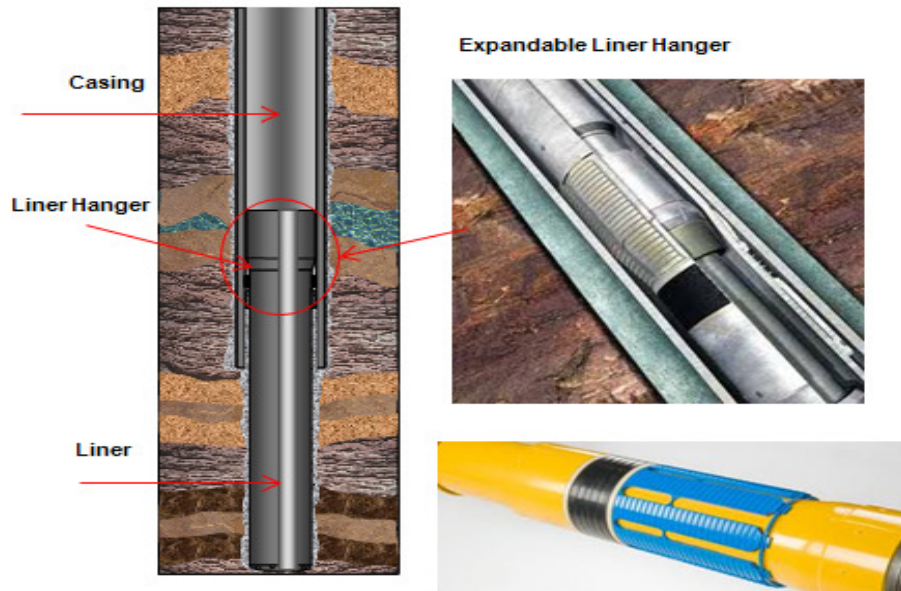
Figure 1. Expandable Liner Hanger System

Because of the mechanical complexity and inherent nonlinearity, developing an expandable liner hanger system represents a challenging engineering problem. Finite element analysis (FEA) using Abaqus® can be effective in reducing development time and cost through design optimization and the need for fewer prototypes.

2. FE Analysis

A finite element (FE) model of an expandable liner hanger system consists of an adjustable swage assembly to expand the hanger body, slip ring to hang the liner load, and a packer to seal in a variable-diameter casing. The swage expands the hanger body, slip ring and packer into the casing, and as the expansion occurs, the slip ring wickers bite into the casing wall and hanger body providing the hanging capacity of the liner hanger. The packer is squeezed in between the hanger body and the casing wall creating an annular, pressure-tight seal.

Figure 2 shows a half section of a FE model of the expandable liner hanger. Due to the size and need of a refined mesh in the slip wicker zone, the typical FE model can have more than 4 million elements. Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing is used to maintain a high quality mesh throughout the analysis in the area of large material deformation. The large

deformation occurs due to slip ring wicker penetration into the casing and hanger body after expansion. Extreme care is required to mesh the penetrated region of the casing and hanger body as ALE formulation limits the deformation of material in the model to the deformation of the elements. ALE was found to be very effective at maintaining the quality of the mesh during analysis in the area of extreme deformation. Figure 3 shows the deformed geometry after expansion. Figure 4 (a) and (b) shows the typical mesh for the assembly and deformed mesh after slip ring wicker penetration, respectively.

The analysis sequence of setting the liner hanger consists of: expanding the hanger body, slip ring, and packer in the casing using the adjustable swage, retrieving the adjustable swage and finally pulling the bottom of the hanger body to determine the hanging capacity of the liner hanger. Abaqus®/Explicit with multiple processors is used to run the analysis.
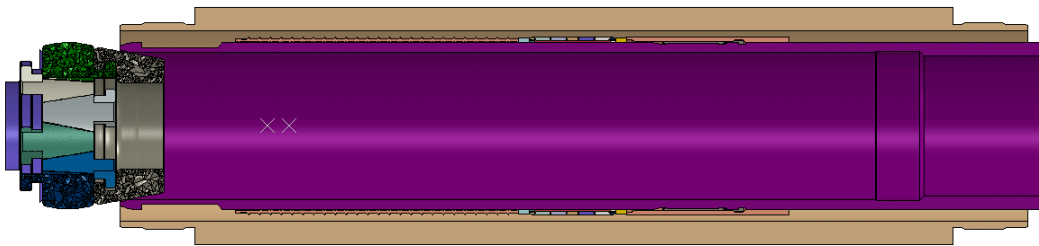

Figure 2. FE Model before expansion
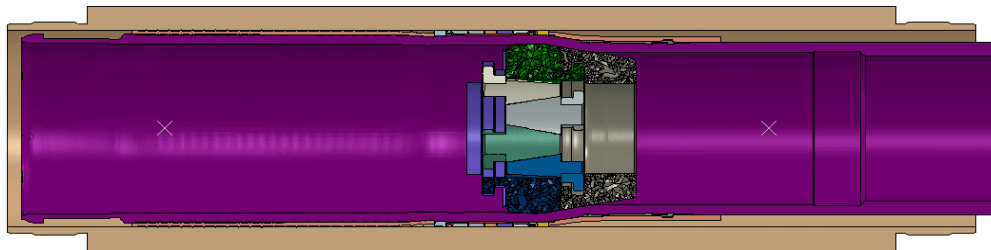
Figure 3. FE Model after expansion

**(a)**   **(b)**
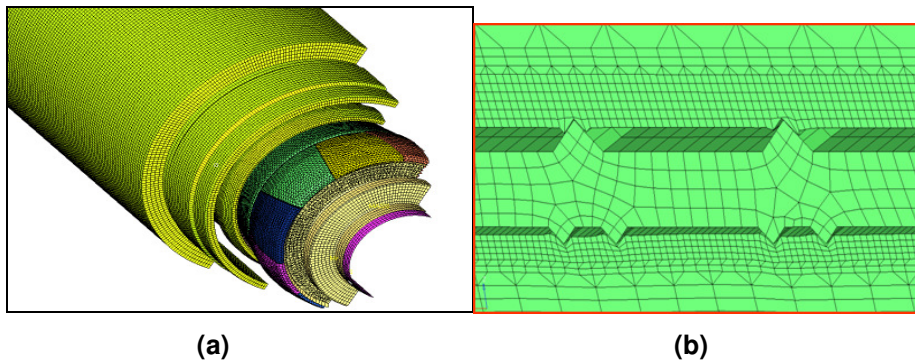
Figure 4. Illustration of FE Mesh

Using the Abaqus® based FEA results, potential designs were evaluated for the performance parameters such as required expansion force, hanging capacity, wickers penetration, stress distribution on swages, and seal integrity for multiple design alternatives of the adjustable swage. Figure 5 shows the typical normalized graph of expansion force for a baseline design and one of the alternative designs with a swage diameter change. Figure 6 shows the hanging capacity comparison for the baseline design and one of the alternative designs where design hanging capacity was increased by 40% over the baseline design.
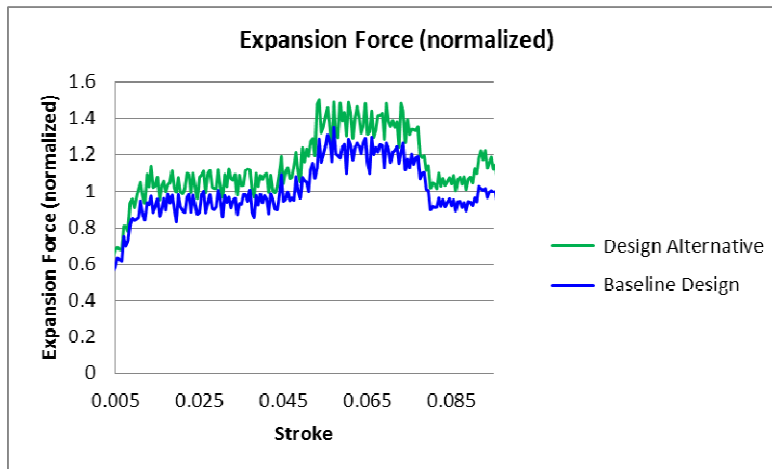

Figure 5. Expansion Force
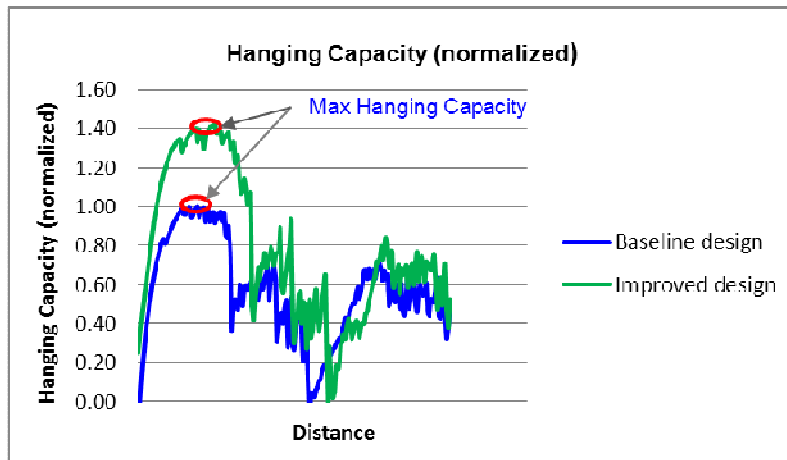
Figure 6. Hanging Capacity

Figure 7 and 8 shows the stresses on the swage assembly, slip ring wicker penetration, and complete liner hanger assembly. With the adjustable swage being a part of the running tool, it is important that the swage design withstand the high stresses from the expansion force. Also, it is required to ensure stresses and plastic strains on other parts of the assembly are within the allowable limits.
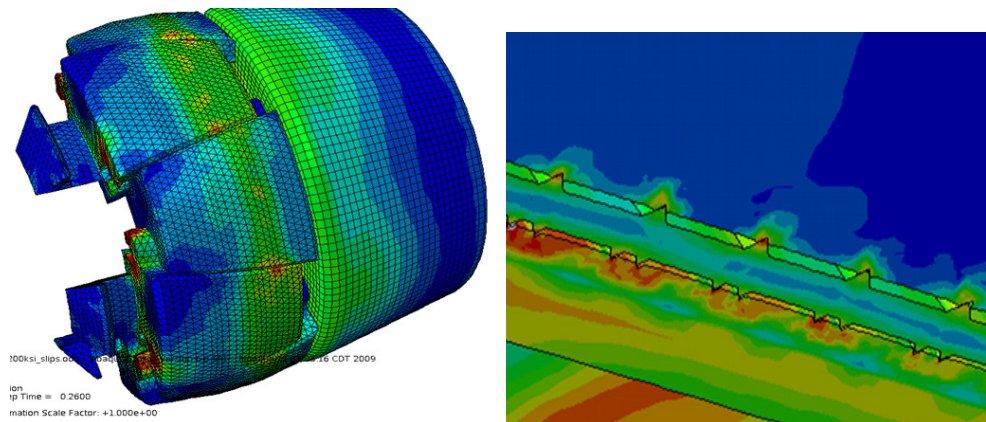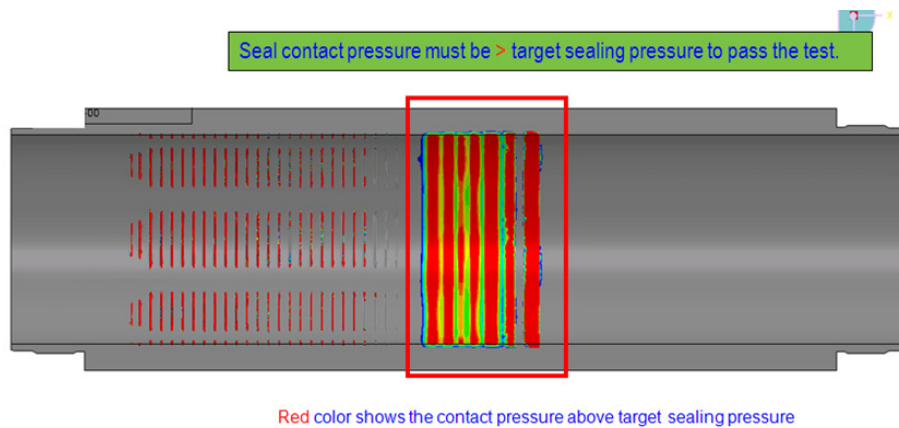

Figure 7. Stresses on Swage and slip ring wicker penetration
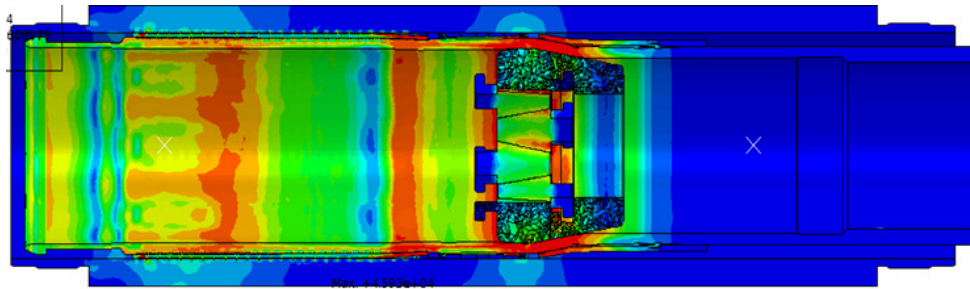
Figure 8. Stress plot

As the seal is fully contained, the seal integrity analysis was very simple and amounted to evaluating the contact pressure within the seal region and determining if the contact pressure was greater than the desired target value. Figure 9 shows the typical seal integrity plot based on the contact pressure of the seal. In general, the modeling for the seal was performed with worst case dimensions to provide a conservative value for the seal integrity. The hanger packer design and swage diameter was finalized based on the comparison of the analytical predictions against the desired performance targets.

Seal contact pressure must be > target sealing pressure to pass the test.

Red color shows the contact pressure above target sealing pressure

Figure 9. Seal Integrity

3. Sensitivity, Optimization and Reliability Assessment

As friction between the hanger body and swage has a significant impact on the expansion force, a sensitivity study was performed to represent proper friction values as corroborated by physical test data. As shown in figure 10, the expansion force is very sensitive and directly proportional to the coefficient of friction between the swage and hanger body, so it is very important to design the casing and swage contact surfaces with low friction. The application of proper friction reducing

surface coatings and lubricants are required to keep the expansion forces within the equipment capacity.
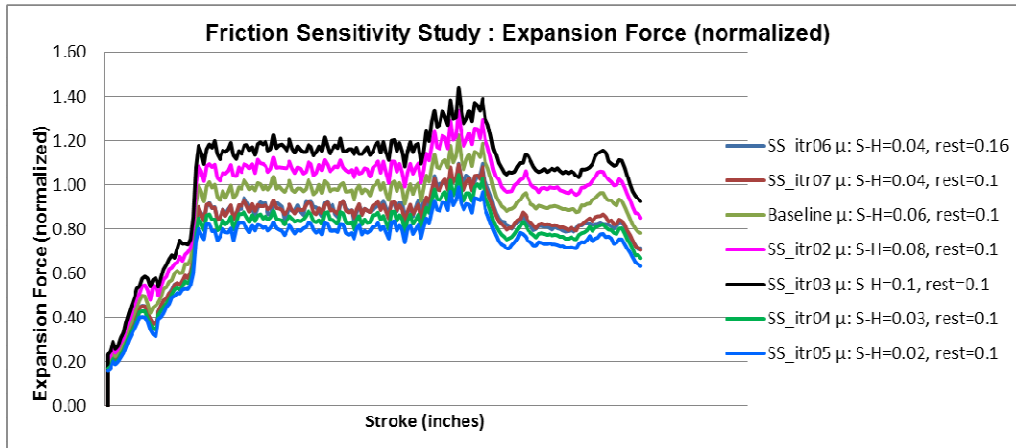

Figure 10. Friction Sensitivity

Since geometry of the slip ring wickers has a significant effect on the liner hanger hanging capacity, a Design of Experiments (DOE) based optimization of the slip ring geometry was performed using HyperStudy® and Abaqus®/explicit software. Full factorial DOE was used for approximation using least squares regression. Figure 11 shows the slip ring geometry and design factors with levels used to run the DOE. Figure 12 shows the response surfaces created based on the DOE.

Figure 11. Design of Experiments (DOE) Variables
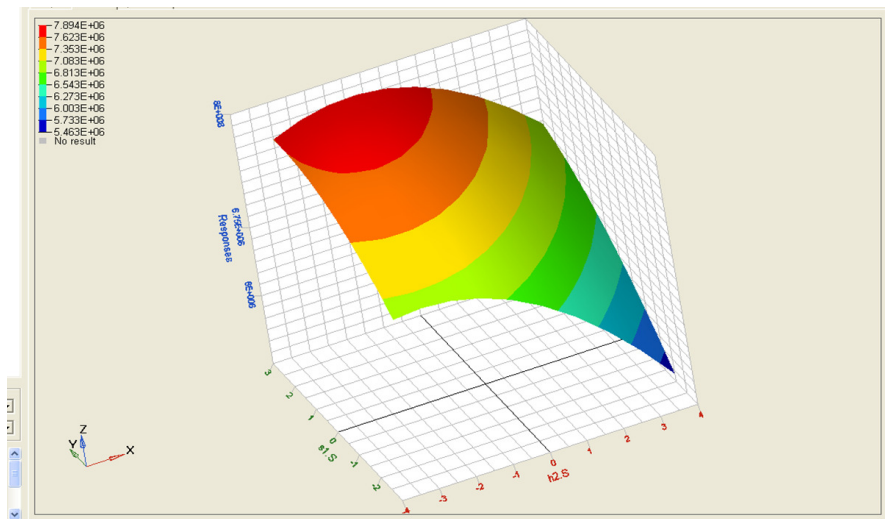
Figure 12. DOE based Response Surface

DOE was one of the most time consuming steps due to the number of experiments and analysis run time. With optimization, the desired hanging capacity for the slip ring geometry was achieved.

A reliability assesment (stochastic study) of the optimized slip ring geometry hanging capacity was also performed based on approximation using HyperStudy®. The Latin hypercube sampling method was used for the stochastic study and the normal statistical distribution of the design variables was assumed. Figure 13 shows the distribution of input value for one slip ring variable, h_1. Finally, we explored the reliability-based optimization by using SORA – Sequential Optimization and Reliability Assessment – a module within HyperStudy® to achieve desired estimated design reliability. The reliability assessment was then used to compare the desired hanging capacity against what the slips could achieve in a consistent, real-world scenario. From the designer standpoint, the reliability assessment can be used as a basis for determining how realistic desired target requirements are compared to what a particular design is capable of reliably achieving.
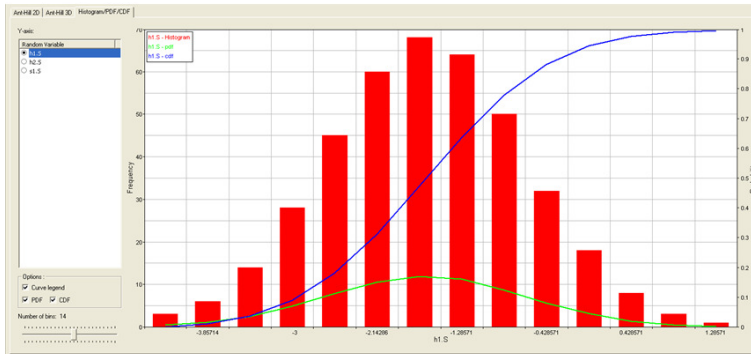
Random Variable Histogram/PDF/CDF

Figure 13. Random variable Histogram/PDF/CDF

4. Laboratory Test Correlation

Analytical challenges such as modeling exact behavior of friction at various contact areas, exact behavior of rubber flow, complex deformation behavior of the wicker penetration, manufacturing variability, and complexity of multi-physics behavior causes some variation between test and analysis results in some of the cases; however, it is observed that FEA results such as expansion force, hanging capacity, and seal integrity correlate fairly well with test data in most of the liner hanger sizes.
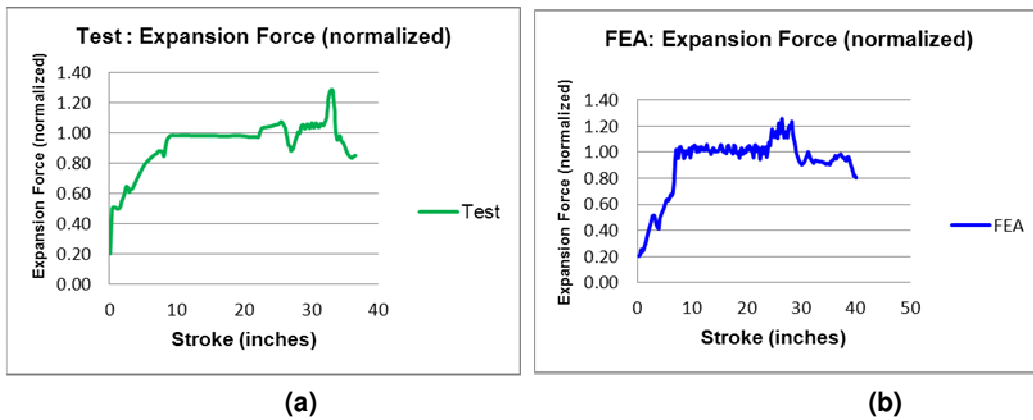

(a)   (b)

Figure 14. Lab Test vs FEA correlation

For an example figure 14(a) and (b) shows the correlation of FEA analysis predictions for the expansion force with laboratory test data for one of the liner hanger sizes.

When considering the baseline test data that was obtained prior to optimization, the optimization predicted an improvement in hanging capacity of 70% (see Table 1). When the optimized design was tested, the results were quite accurate with less than 4% error in the predicted value versus the tested value, and in every lab test, the tested hanging capacity successfully exceeded the value predicted in the reliability assessment (see Table 1).

For the packer seal, the test results when compared to the analysis predictions were also very favorable. The analytically predicted value was above the desired target value. The lab tests confirmed that the design was able to achieve the desired performance targets each time, but due to the nature of the test setup, the pressure tests were not tested to failure.

Table 1. FEA vs Lab Test Hanging Capacity Correlation (normalized)

	Baseline Design Lab Test	FEA prediction for Optimized Design	FEA prediction for Optimized Design based on Reliability Assesment	Lab Test #1 for Optimized Design	Lab test #2 for Optimized Design
Hanging Capacity	1	1.7	1.29	1.76	1.63
% improvement from baseline	....	70%	.....	76%	63%
% error from FEA prediction for optimized design	.....	.....	.....	3.8%	-3.9%
% difference from FEA prediction for optimized design based on Reliability Assesment	....	.....	.....	37%	27%

5. Conclusion

Despite some challenges, Abaqus®/explicit has been successfully used to understand the complex physics of the expandable liner hanger system and optimize both the adjustable swage and slip ring designs. It helped us to study the effects of various design parameters of the adjustable swage, slip ring and packer and how those parameters affect performance such as the sealing integrity, hanging capacity, and other performance targets—even before prototype testing. This reduced the number of prototype tests by 60% when compared to similar design projects where these FEA methods were not utilized. As a result, FEA using Abaqus® helped us to accelerate the development of the expandable liner hanger system by minimizing the number of prototypes needed and allowed us to maximize the performance while at the same time helping us to understand some of the design limits.

6. Acknowledgements